# POWER-OPTIMISED MULTI-RADIO NETWORK UNDER VARYING THROUGHPUT CONSTRAINTS FOR RURAL BROADBAND ACCESS

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## ABSTRACT

The use of complementary radio access technologies within a network allows the advantages of each technology to be combined to overcome individual limitations. In this paper we show how 5 GHz and "TV White Space" overlay networks can be combined to provide fixed wireless access coverage within a rural environment. By creating a model of the whole network we derive the optimum assignment of stations between the two overlay networks to maximise the capacity of individual stations given a desired individual station data rate. Through simulation we show how the power consumption of a base station can be minimised by dynamically adjusting station assignments based on network data rate requirements changing over the course of a day.

***Index Terms*—** heterogeneous networks, energy efficiency, TV white space, cell breathing, rural broadband access.

## 1. INTRODUCTION

Providing internet access in rural communities is difficult due to the terrain, low population density and lack of infrastructure. Wireless links based on WiMAX [1] and IEEE 802.11 [2, 3] have been successfully used world-wide for rural access. The wide channel bandwidths of these technologies offering large data rates are contrasted by restrictions to short range and line of sight (LOS) connections due the propagation characteristics of the frequency bands used [4]. The "TV White Space" (TVWS) band is widely seen as an opportunity to deliver rural broadband, with the ability to cover long distances and non-LOS channels [4, 5]; however, throughput can be limited by a small channel bandwidth.

The minimisation of power consumption in base stations for rural broadband delivery is important, as this can allow base stations to be powered by renewable energy sources [3, 4]. This has stimulated power savings in the design of a single network [6]. The recent use of heterogeneous multiple radio access networks (RANs) is not just regarded as a low cost solution to increase capacity [7], but also offers the opportunity for reducing power consumption using complementary technologies whilst maintaining quality of service [8, 9, 10]. The desired data rate for a user can be employed as a driver for access technology selection, and has been demonstrated to reduce power consumption in mobile devices [11].

Cell breathing is a well known method for load balancing in cellular networks [12, 13], where cells can expand or contract to control the number of users associated with a base station, thus controlling capacity of the network. Cell breathing can also be used as an energy saving feature, allowing cells to be turned off when capacity is not required [14, 15], thus enabling such networks to be powered by renewables [16]. The diurnal fluctuation in network traffic patterns has been proposed as trigger for scaling network capacity through breathing [15, 17], increasing capacity at the expense of power consumption during peak demand times.

In this paper, we specifically address the model of a rural community served by two RANs, such as created by a WindFi base station [4] that uses a combination of an IEEE 802.11 RAN in the 5 GHz band and an overlay ultra-high frequency (UHF) RAN in TVWS. The 5 GHz RAN provides high capacity over a short range whilst the UHF RAN handles the "hard to reach" households. Based on the ideas of cell-breathing and diurnal network traffic pattern we propose a scheme to adjust the assignment of users to specific RANs in order to minimise the overall power consumption at any given point in time, while heeding constraints on the transmit power due to regulatory restrictions and on the data rate due to a required minimal fulfilment of a target data rate.

In order to describe this optimisation approach, this paper is structured as follows. Sec. 3 presents a model of the network used to determine the impact of an assignment. Sec. 4 describes optimising the assignment to maximise station data rates. Sec. 5 shows through simulation how the assignment of stations within a community can be optimised and the base station power consumption minimised as the station assignment dynamically changes with traffic requirements.

## 2. PROBLEM FORMULATION

We assume a community of households, $\mathcal{S}$, with individual households denoted as stations $s \in \mathcal{S}$. The stations in $\mathcal{S}$ are ordered in ascending radial distance — and therefore in ascending path loss according to the propagation models defined later — from a single base station serving the community via a set $\mathcal{A} = \{a_{\rm u}, a_{\rm g}\}$ of radio access networks. A UHF network $a_{\rm u}$ and a GHz network $a_{\rm g}$ are available, and stations associated with each RAN are contained in the sets $\mathcal{S}_{\rm u}$ and $\mathcal{S}_{\rm g}$. All stations must be assigned to only one RAN such that $\mathcal{S}_{\rm g} \cup \mathcal{S}_{\rm u} = S$ and $\mathcal{S}_{\rm g} \cap \mathcal{S}_{\rm u} = \emptyset$. The assignment of stations in the network is therefore described as $\mathcal{N} = \{\mathcal{S}_{\rm g}, \mathcal{S}_{\rm u}\}$.

The problem addressed in this paper is to determine the optimum assignment $\mathcal{N}$, which will depend on parameters of the network and the environment, and will be driven by time-varying throughput requirements placed on $\mathcal{A}$ by the stations in $\mathcal{S}$. Below, Sec. 3 will describe the network model, where the impact of $\mathcal{N}$ on the individual data rates and the power consumption at the base station is derived. The cost function for optimising $\mathcal{N}$ will then be defined in Sec. 4.

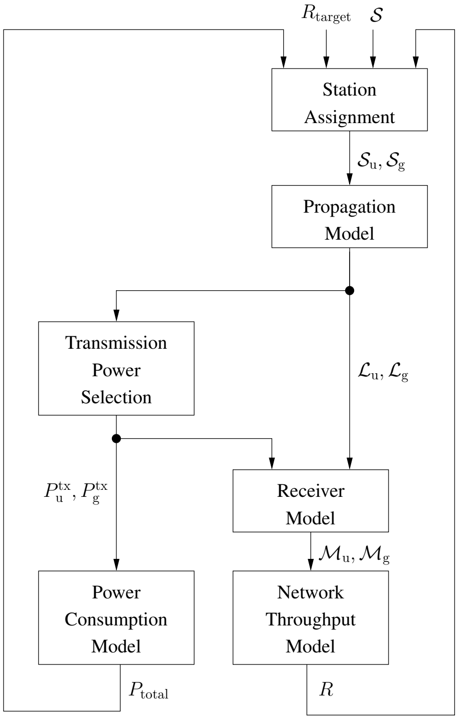


**Fig. 1**. Network adjustment model.

## 3. NETWORK MODEL

A model of the network, as outlined in Fig. 1, relating the station assignment $\mathcal{N}$ to an expected minimum station data rate $R$ and power consumption $P_{\text{total}}$ is used to study the impact of station assignments. Each station in $\mathcal{S}_a$, $a \in \{\text{u}, \text{g}\}$, has a corresponding path loss calculated using a path loss model, $f_l : \mathcal{S}_a \rightarrow \mathcal{L}_a, \forall a \in \mathcal{A}$. The path losses for the stations and for each RAN form the $\mathcal{L}_a$, which, for a given assignment $\mathcal{N}$, determines the transmission power $P_a^{\text{tx}}$ for RAN $a$. Note that $P_{\text{g}}^{\text{tx}}$ determines which stations can be reached by the GHz RAN, with the remaining stations assigned to $\mathcal{S}_{\text{u}}$. If transmit power permits, the preference of any station $s$ is to associate with $a_{\text{g}}$.

Each station can run at one modulation and coding scheme (MCS) from a feasible set, $\mathcal{M}^{\text{avail}}$. The MCS used for each station on each RAN, $f_m : \mathcal{L}_a \rightarrow \mathcal{M}_a, \forall a \in \mathcal{A}$, depends on the path loss of the station and transmission power of the RAN. Given a set of stations MCS levels for each RAN, $\mathcal{M}_a$, the minimum data rate for an individual station within the network, $R$, is calculated using a network throughput model. The base station power consumption $P_{\text{total}}$ is a function of the transmit powers, which, together with the individual station data rate $R$, can be used to select a station assignment $\mathcal{N}$ given a target data rate $R_{\text{target}}$. Below, the various models and components contained in the network model are analysed in order to operate the overall approach outlined in Fig. 1.

### 3.1. Propagation Model

The propagation model for Fig. 1 uses a simplified formula [18] to estimate the path loss between a transmitter and receiver. For stations $s$ at a distance $d$ from the base station, the path loss measured in dB is

$$L_{s,a} = K_a \cdot \left(\frac{d}{d_0}\right)^{-\gamma} \cdot \Psi \quad , \tag{1}$$

where $\gamma$ is the path loss exponent and $\Psi$ a log-normal distributed random variable to model shadow fading. The constant $K_a$ depends on antenna characteristics and the average channel attenuation, and is here set to the free-space path gain at a reference distance $d_0$ in the antenna's far field. Assuming omni-directional antennas,

$$K_a = \left(\frac{c}{4\pi d_0 f_a}\right)^2 \tag{2}$$

for RAN $a$ operating at frequency $f_a$. With (1) and (2), the parameters $\mathcal{L}_a$ in Fig. 1 are calculated.

### 3.2. Transmission Power Selection

The transmit powers of $\mathcal{A}$, $P_a^{\text{tx}}$, depend on the assignment $\mathcal{N}$ and the path losses for stations in $\mathcal{S}$ and their association with either of the RANs. The crucial component is the GHz network $a_{\text{g}}$, which must provide the transmission power $P_{\text{g}}^{\text{tx}}$ to support the $|\mathcal{S}_{\text{g}}|$ stations associated with it.

To determine $P_{\text{g}}^{\text{tx}}$, we consider the minimum required transmit power $P_{s,m}^{\text{tx,min}}$ to establish a connection with station $s$ on the GHz RAN with MCS scheme $m$,

$$P_{s,m}^{\text{tx,min}} = L_{\text{s,g}} + P_m^{\text{rx}} - G_{\text{rx}} \quad , \tag{3}$$

where the receive antenna gain $G_{\text{rx}}$ and the minimum receive signal level to support MCS level $m$, $P_m^{\text{rx}}$, are measured in dB. The combination of all possible minimum transmission powers for each station and modulation scheme are members of the set $\mathcal{P}^{\text{tx,min}}$.

When $i$ represents the index of $s$ in $\mathcal{S}_{\text{g}}$: $i \in \{1 \ldots |\mathcal{S}_{\text{g}}|\}$, then the maximum transmission power required to associate station $i$ and not $i+1$ is given by

$$P_i^{\text{tx,max}} = \max\left\{P^{\text{tx,min}} \in \mathcal{P}^{\text{tx,min}} | P^{\text{tx,min}} < P_{i+1,0}^{\text{tx,min}}\right\} \quad , \tag{4}$$

where $m = 0$ is the minimum MCS required for a reliable connection. Another station is reassigned between RANs to allow extrapolation for $i = |\mathcal{S}_g|$. Therefore, for a desired number of stations on the GHz RAN, $|\mathcal{S}_g|$,

$$P_{\text{g}}^{\text{tx}} = P_{|\mathcal{S}_{\text{g}}|}^{\text{tx,max}} \tag{5}$$

represents the required transmission power.

The transmission power for the UHF RAN $a_{\text{u}}$, $P_{\text{u}}^{\text{tx}}$, is 30 dBm which is a possible limit for TVWS transmissions recommended in the Cambridge TVWS Trial [19]. This is assumed to create a reliable connection for all stations.

### 3.3. Receiver Model

For a given transmission power and path loss, the receive power for station $s$ on RAN $a$ is given by

$$P_{s,a}^{\text{rx}} = P_a^{\text{tx}} - L_{s,a} + G_{\text{rx}} \quad , \tag{6}$$

assuming all quantities are measured in dB. The MCS levels for a set of stations in a RAN is denoted as $\mathcal{M}_a$. Each MCS rate has a corresponding minimum receive power which is obtained through a lookup table. The set of minimum receive powers for all possible MCS levels is denoted as $\mathcal{P}^{\text{mcs,rx}}$. For each station receive power, the MCS rate used by station $s$, $M_{s,a}$, is determined by the range within which $P_{s,a}^{\text{rx}}$ falls. The MCS receive power $P_{s,a}^{\text{mcs,rx}} \in \mathcal{P}^{\text{mcs,rx}}$ best suited for station $s$ is

$$P_{s,a}^{\text{mcs,rx}} = \max\left\{P^{\text{mcs,rx}} \in \mathcal{P}^{\text{mcs,rx}} | P^{\text{mcs,rx}} \leq P_{s,a}^{\text{rx}}\right\} \quad . \tag{7}$$

Therefore, the MCS level for the set of stations in each RAN is $f_m : \mathcal{P}_a^{\text{mcs,rx}} \rightarrow \mathcal{M}_a$, which according to Fig. 1 provides the input to the network throughput model.

### 3.4. Network Throughput Model

Given a set of MCS values for each station on a RAN, the network throughput model calculates the expected User Datagram Protocol (UDP) downlink data rate for each station using a model of the IEEE 802.11 MAC layer in point coordination function (PCF) mode [20]. This model is used for both networks.

With the expected data rate $R_a$ in bits/s (bps) for each of the $N = |\mathcal{S}_a|$ stations in $\mathcal{S}_a$,

$$R_a = \frac{L_{\text{DATA}}}{T_{\text{PCF},a}} \quad , \tag{8}$$

the minimum data rate for an individual station in the network, $R$, is given by

$$R = \min\left(R_a\right), \forall a \in \mathcal{A} \quad . \tag{9}$$

In (8), $L_{\text{DATA}}$ is the length of the data packet in bits, which for simplicity is assumed to be uniform across all stations to simulate a congested network. Further, the total time required for a PCF exchange between the point coordinator and all associated stations is

$$\begin{aligned} T_{\text{PCF}} &= T_{\text{PIFS}} + T_{\text{BEACON}} \\ &+ \sum_{n=0}^{N-1}\left(T_{\text{DATA\_CF\_POLL}}[n] + T_{\text{CF\_ACK}}[n]\right) \\ &+ (2N+1)\, T_{\text{SIFS}} + \max\left(T_{\text{CF\_END}}\right) \quad , \end{aligned} \tag{10}$$

where for each station

$$\begin{aligned} T_{\text{DATA\_CF\_POLL}} &= T_{\text{PRE}} + T_{\text{PHY}} + \left\lceil \frac{22 + L_{\text{MAC}} + L_{\text{DATA}}}{N_{\text{DBPS}}} \right\rceil \\ T_{\text{CF\_ACK}} &= T_{\text{PRE}} + T_{\text{PHY}} + \left\lceil \frac{22 + L_{\text{MAC}}}{N_{\text{CBPS}}} \right\rceil \\ T_{\text{CF\_END}} &= T_{\text{PRE}} + T_{\text{PHY}} + \left\lceil \frac{22 + L_{\text{CF\_END}}}{N_{\text{CBPS}}} \right\rceil \end{aligned} \tag{11}$$

are derived from standard IEEE 802.11a parameters and values. The number of data bits per symbols $N_{\text{DBPS}}$ and number of control bits per symbols $N_{\text{CBPS}}$ depend on the MCS index. The length of the beacon is denoted by $T_{\text{BEACON}}$, $T_{\text{PIFS}}$ is the PCF interframe space, $T_{\text{SIFS}}$ the short interframe space, $T_{\text{PRE}}$ the preamble length, $T_{\text{PHY}}$ the signal symbol overhead in the physical protocol unit, $L_{\text{MAC}}$ is the number of bits of MAC data within the Physical Layer Convergence Protocol Service Data Unit (PSDU), and $L_{\text{CF\_END}}$ is the length of the contention free period end frame contents in bits. For a channel bandwidth $B$, $T_{\text{SIFS}}$, $T_{\text{PIFS}}$, $T_{\text{PRE}}$ and $T_{\text{PHY}}$ are scaled by $\frac{20\text{MHz}}{B}$ [20].

### 3.5. Power Consumption Model

Based on lab measurements on the WindFi system [4] for both GHz and UHZ radios, the power consumption of a radio is approximated by a function of the transmit power $P_a^{\text{tx}}$ and transmit antenna gain $G_{\text{tx}}$,

$$P_{\text{radio},a} = \alpha_a \left(P_a^{\text{tx}} - G_{\text{tx},a}\right)^{\beta_a} + \gamma_a \tag{12}$$

The coefficients $\alpha$, $\beta$ and $\gamma$ in (12) differ for each RAN, with measured values reported later in Tab. 1. This leads to

$$P_{\text{total}} = \sum_{\forall a \in \mathcal{A}} P_{\text{radio},a} \tag{13}$$

as the total power consumption of the base station.

## 4. OPTIMUM STATION ASSIGNMENT

The optimum station assignment minimises the difference between the time-varying target data rate, $R_{\text{target}}$, and the data rate $R(\mathcal{N}_i)$ provided by a specific station assignment $\mathcal{N}_i = \{\mathcal{S}_{\text{u},i}, \mathcal{S}_{\text{g},i}\} \in \mathcal{N}^{\text{All}}$ where $\mathcal{N}^{\text{All}}$ is a set of all possible station assignments, with $|\mathcal{N}^{\text{All}}| = |S| + 1$. Achieving only a lower rate will penalise station users, while a higher rate utilises more transmit power than necessary. Therefore the optimum assignment $\mathcal{N}_{\text{opt}}$ can be obtained by solving the constrained optimisation problem

$$\begin{aligned} \mathcal{N}_{\text{opt}} &= \arg\min_{\mathcal{N}_i \in \mathcal{N}^{\text{All}}} |R_{\text{target}} - R(\mathcal{N}_i)| \quad , \\ \text{s.t.} \quad & R(\mathcal{N}_i) \geq R_{\text{target}} \\ & P_a^{\text{tx}} \leq P_{a,\max}^{\text{tx}}, \forall a \in \mathcal{A} \quad , \end{aligned} \tag{14}$$

where $P_{a,\max}^{\text{tx}}$ is the maximum permissible transmission power. By seeking to keep the data rate to a permissible minimum, (14) will also directly minimise transmission power.

The optimisation problem in (14) is not guaranteed to be convex, and a closed form solution can be challenging. Therefore, below we first identify a feasible set of assignments that satisfy the constraints, and thereafter perform a graphical, but unconstrained optimisation over this feasible set.

## 5. SIMULATION AND RESULTS

In this section we demonstrate through simulation how a station assignment can be optimised (14). Furthermore we show how dynamically optimising the assignment based on instantaneous network capacity requirements can minimize the total power consumption. We use a scenario of a base station serving 20 stations. Based the WindFi parameters [4] two networks are used to provide connectivity,

- a UHF RAN at $f_{\text{u}} = 763$ MHz with 5 MHz bandwidth
- a GHz RAN at $f_{\text{g}} = 5.66$ GHz with 20 MHz bandwidth

Below, based on a distribution model in Sec. 5.1, the network model of Sec. 3 is applied to an ensemble of $10^5$ sets $\mathcal{S}$. The impact of station assignment is presented in Sec. 5.2, and Sec. 5.3 shows how breathing the GHz RAN over a 24 hour period reduces base station power consumption.

### 5.1. Station Distribution

The majority of households are located close to the "hub" of the community, where a base station is typically situated. Fig. 2 shows the distribution of 500 households from community base stations on the island of Tiree. A circularly symmetric normal distribution depending on $x$ (North) and $y$ (West) coordinates with the base station at the origin has been fitted with good approximation to the relative distribution of households in Fig. 2, such that the probability density function for $r = \sqrt{x^2 + y^2}$ is given by

$$\phi(r) = \frac{1}{2\pi\sigma_r^2} \exp\left\{-\frac{1}{2}\left(\frac{r}{\sigma_r}\right)^2\right\} \quad . \tag{15}$$

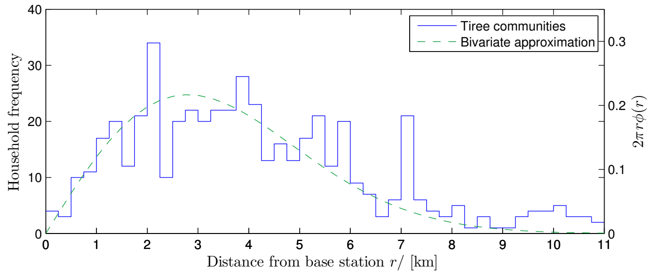


**Fig. 2**. Histogram of household distance from base station on Tiree.

| Parameter | Value |
|---|---|
| $\gamma$ | 2.3 |
| $d_0$ | 1 m |
| $\sigma_x$ | 2.8 km |
| $f_g, f_u$ | 5660 MHz, 763 MHz |
| $\mathcal{P}^{\text{mcs,rx}}$ | $\{-91, -90, -89, -86, -83, -79, -73, -69\}$ dB |
| $L_{\text{DATA}}$ | 2312 bits |
| $\alpha_g, \beta_g, \gamma_g$ | 3.575e-6, 3.78, 2.917 |
| $\alpha_u, \beta_u, \gamma_u$ | 1.247e-3, 2.357, 3.216 |
| $G_{tx}, G_{rx}$ | 10 dB |
| $P^{\text{tx,max}}$ | 30 dB |

**Table 1**. Simulation parameters.

Fig. 2 shows the probability of finding a household between radii $r$ and $r + dr$ with $\sigma_r = 2.8$ km, which closely resembles the observed distribution, and was therefore used as part of the simulation parameter set in Tab. 1.

### 5.2. Impact of Station Assignment

Fig. 3 shows the station data throughput for each RAN for all feasible sets of assignments which satisfy the constraint of a valid GHz RAN transmission power, $P_g^{\text{tx}} \leq P_{\text{max}}^{\text{tx}}$. The six stations furthest from the base station cannot be served by the GHz RAN. The minimum combined station capacity increases by 106%, from 0.50 Mbps when all stations are served by the UHF RAN to 1.04 Mbps in case stations are optimally assigned between RANs.

As discussed in Sec. 4 the optimum station assignment can be viewed graphically from Fig. 3, the case of optimum assignment is $|S_{\text{opt},g}| = 12$. Intuitively given that the GHz RAN has four times the bandwidth of the UHF RAN, the GHz RAN should serve as many users as the transmission power constraint allows. Our results disagree with this statement as the optimum number of stations to serve with GHz is only 60% of the stations. This is due to the better propagation characteristics of the UHF RAN leading to stations being served at a higher MCS rate than those by the GHz RAN.

### 5.3. GHz RAN Breathing to Minimize Power Consumption

To obtain realistic figures for the time-varying target rate $R_{\text{target}}$ that drives (14), we have used the residential DSL downlink traffic presented in [17] as a network utilisation $u \in [0, 1]$ over a day, as shown in Fig. 4. The target data rate for optimisation as discussed in Sec. 4 can be derived from this utilisation by normalising the optimum data rate for assignment set $\mathcal{N}$, such that

$$R_{\text{target}} = u \cdot R(\mathcal{N}_{\text{opt}}) \quad . \tag{16}$$

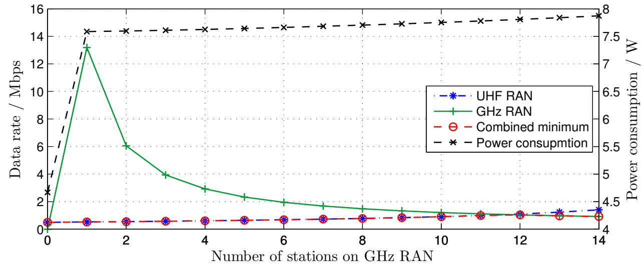


**Fig. 3**. Individual station capacity on each RAN and base station power consumption given possible valid RAN assignments.

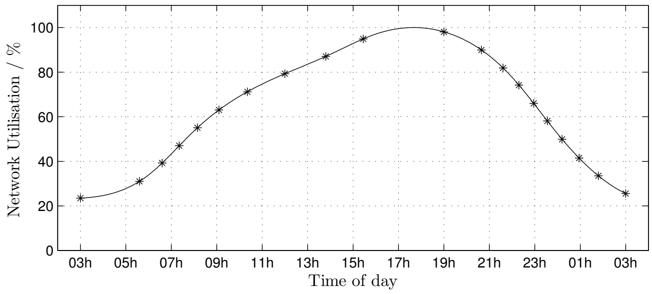


**Fig. 4**. Daily utilisation on a residential DSL network [17].

The power consumption increases from 2.4 W, when UHF is solely serving every station and the GHZ RAN is turned off, to a maximum of 8 W when 14 stations are served by the GHz RAN. Fig. 3 is then used to perform the unconstrained optimisation aluded in Sec. 4 to decreasing the number of stations on the GHz RAN as much as possible, as long as $R_{\text{target}}$ is met, thus minimising the power consumption.

### 5.4. Benchmarks and Discussion

Fig. 5 (top) shows the required capacity and capacity offered when using different dynamic and static assignment schemes. In general, the data rate provided by the optimised scheme closely follows the target data rate from above, thus satisfying the constraint and minimising transmission power. Fig. 5 (middle) compares the power consumption, where the optimised scheme exhibits a step up in power when the GHz RAN is required to satisfy the throughput demand during the peak time of the day. The fluctuating optimum station assignment is depicted in Fig. 5 (bottom).

Looking at extreme assigments, when only the UHF RAN is used, the power consumption of the network is minimised but it cannot meet the capacity requirement during peak times from 7.30h to 0.30h. Maximising the size of the GHz RAN serves all GHz users at the highest MCS rate but requires the greatest power consumption. Due to the number of stations on the GHz RAN, the network capacity in this case is lower than at the optimum assignment.

Fig. 5 also shows a case where the assignment is fixed to the maximum throughput obtained from Fig. 3. In this case the power consumption is constantly high even though the data rate is not required at all times. Dynamically changing the assignment, as proposed with the solution to (14), optimises the system at each moment w.r.t. power consumption, providing reduction of 12.7% compared to using the above fixed assignment.

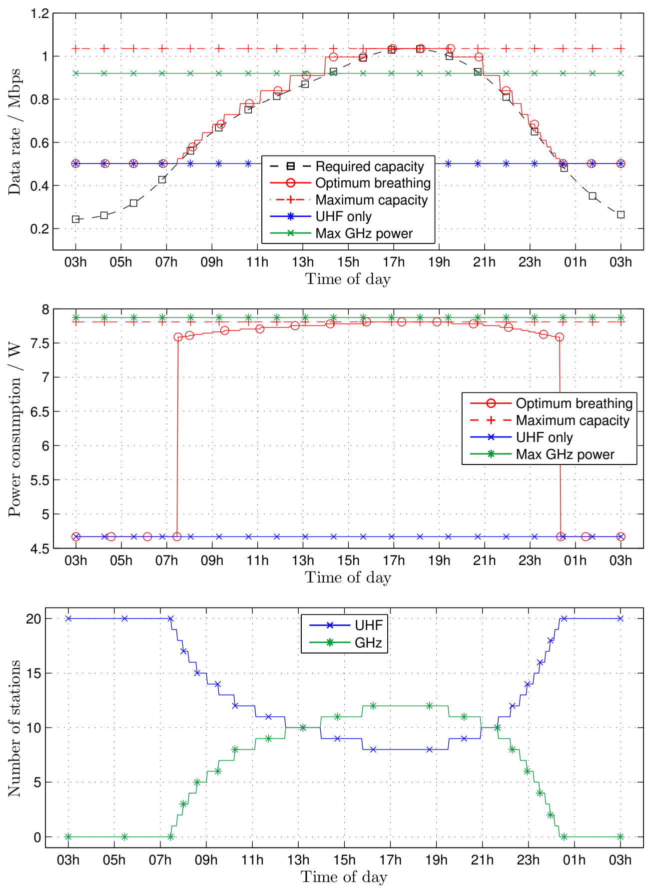


**Fig. 5**. Results of solving (14) in 15 min. intervals, showing (top) the required and offered capacity, (middle) the total network power consumption and (bottom) the station assignment.

## 6. CONCLUSION

In this paper we have presented a model to optimise the station assignment in a dual RAN situation, comprising a 5 GHz and UHF TVWS network, with respect to minimum power consumption while fulfilling transmit power constraints and the minimal achievement of a target data rate prescribed by a utilisation pattern. We have shown how the assignment of stations to each RAN can be optimised to maximise individual station data rates. Interestingly, this optimum assignment differs from intuitively assigning as many stations as possible to the higher bandwidth GHz RAN, as the UHF RAN can reach stations at the edge between both network assignments with higher MCS schemes. We have further demonstrated how power consumption can be reduced by dynamically changing the assignment based on traffic requirements.

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